Magnetic Augmented Self-sensing Flexible Electroadhesive Grippers

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***Abstract*—Current electroadhesion (EA) grippers cannot be used to lift objects with limited contact areas. Current electromagnetic adhesion (MA) grippers cannot be used to grip non-ferrous materials. Here we combine EA and MA into a monolithic, electrically controllable, flexible, and hybrid Electro/Magneto-adhesive (E/MA), to offer EA grippers augmented with magnetoadhesion and MA grippers augmented with electroadhesion. This E/MA was achieved by exploiting two intertwined coplanar coils inspired by Tesla's flat bifilar coil. By appropriate electrical connections an electromagnetic field is generated – driving magnetic attraction – or an electric field is generated – delivering electroadhesion – or both fields can be generated simultaneously. As a result, the E/MA grippers can not only be used to lift ferrous and non-ferrous materials but also low-density objects such as office paper clips. We also present a customized capacitance measurement method to enable an autonomous material handling system without embedding external sensors. E/MA grippers have the potential to expand the capabilities and impact of soft robotics and industrial gripper systems.**

***Index Terms*—Soft Sensors and Actuators, Grippers and Other End-Effectors, Grasping, Electroadhesion, Exteroceptive sensing, Flexible electroadhesive gripper, Flexible electromagnetic gripper**

I. INTRODUCTION

CONTROLLABLE, reliable, and robust robotic gripping and manipulation technologies are of significant importance in manufacturing automation applications such as material handling in assembly lines. Robotic gripping methods are usually classified into four categories [1]: 1) impactive methods, including jaws and clamps, 2) ingressive methods, including pins and hackles, 3) astrictive methods, including suction, magnetoadhesion, and electroadhesion, and 4) contigutive methods, including chemical and thermal adhesion mechanisms. Each technology has its strengths and weaknesses and has its own specific applications [1]. Electroadhesion (EA) and electromagnetic adhesion (MA) are two commonly used astrictive and electrically controllable gripping methods.

EA is produced by applying a high voltage (typically in a range of 0.2 - 20 kilovolts) across pairs of electrodes embedded in a dielectric material, and the resultant high electric field creates an electrically controllable adhesion force on both conductive, semi-conductive, and insulating substrates [2-10]. EA is a promising adhesion and material handling technology as it has several key advantages including: 1) the energy consumption of EA systems is low since, although they rely on the application of a high voltage, they consume very low current; 2) EA grippers can be fabricated using lightweight materials and simple structures; 3) EA grippers can be easily fabricated into flexible [7-8] and stretchable forms [9-10], enabling them to lift delicate objects and non-flat surfaces.

Fig. 1. Electro/Magneto-adhesive (E/MA) grippers. (a) The fundamental design of a monolithic and multi-modal E/MA gripper, with electric connections. (b) A flexible E/MA sheet gripper bent by hand. (c) Grasping magnetically susceptible (metal paper clips, total 0.80 g) and insusceptible (fabrics pieces, total 0.62 g) objects simultaneously using the E/MA gripper at 4.8 kV (high-voltage-low-current input) and 8 A (low-voltage-high-current input).

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The magnitude of EA forces is, however, significantly affected by the contact area, manifesting that it is challenging for current EA grippers to lift objects with limited contacting areas such as springs, pins, and office paper clips. MA grippers can be used to lift ferrous materials with small contacting areas, although their power consumption is relatively large since the magnetic field is dependent on a continuous flow of current (usually in an order of amps).

Previously, Feddema *et al.* developed combined electrostatic and electromagnetic grippers for microscale assembly applications, where EA was used for adhesion and MA was used for repulsive quick release [11]. Monkman *et al.* presented an elastomeric magnetoactive electret via a 6D printing approach [12]. Here we combine EA and MA into a monolithic, electrically controllable, flexible, and hybrid Electro/Magneto-adhesive (E/MA, see Fig. 1 (a)), for more versatile mesoscale gripping applications. We present an easy-to-implement and cost-effective fabrication solution by winding two planar spiral of insulated electric wires and then bonding them together, resulting in flexible and bendable E/MA grippers (see Fig. 1 (b)). This flexibility has increased the versatility of the gripper so that it can be used to grip non-flat surfaces and makes it safer for interaction with delicate objects which conventional rigid MA and EA grippers cannot deal with. By selectively powering the ends of the coils, multimodal adhesion can be obtained. As shown in Fig. 1 (a), MA alone can be achieved by closing s1 and s2 and opening s3; EA alone can be achieved by closing s3 and opening s1 and s2; concurrent EA and MA can be achieved by closing s1, s2 and s3. The resulting E/MA is able to produce electroadhesives augmented with magnetoadhesion and magnetoadhesives augmented with electroadhesion. Consequently, the E/MA gripper can not only be used to lift soft materials such as fabrics, but also low-density objects such as metal springs and pins, and even both types of materials at the same time (see Fig. 1 (c) and the supplementary video), a capability beyond conventional EA and MA grippers.

The main contributions of this paper include: 1) the presentation of the E/MA (a hybrid adhesive) concept, with different control strategies and designs, to extend both EA and EMA capabilities; 2) the development of a new, cost-effective, and flexible EA, MA, and EM/A fabrication solution by directly winding two insulated electric wires into a planar bifilar spiral shape; and 3) the development of a customized exteroceptive and autonomous EA material handling system without embedding any external sensors (see the supplementary video).

The reminder of this article is organized as follows. The design and characterization of the E/MA gripper is described in section II. The design and development of a self-sensing and autonomous material handling system is presented in section III. E/MA geometrical, other alternative design considerations, and magnetic field distribution FEA simulation are discussed in section IV. Conclusions, outlining key findings and future work are summarized in section V.

II. Design and characterization of the E/MA gripper

A. Concept design and wiring strategies

The simplest and most elegant design to achieve the proposed E/MA multimodal gripper is shown in Fig. 2, which is based on Tesla's flat bifilar coil design [14]. Individual EA function can be achieved by connecting a high voltage between the red and black wire ends (see Fig. 2 (a)). Individual MA function can be achieved by connecting a low voltage between the two ends of either the red or black wires (see Fig. 2 (b) and (c)), or both in series or parallel. The bifilar coil incorporates two intertwined planar coils, commonly connected such that the circumferential currents in neighboring wires run in opposite directions, thereby cancelling the magnetic fields that are generated. While this was advantageous for Tesla's original application, we connect the bifilar coil such that circumferential currents in neighboring wires run in the *same* direction (see Fig. 2 (d)), thereby maximizing the magnetic force generated. Simultaneous EA and MA function can be achieved by connecting one high-voltage/low current (HVLI) power supply and one or two low-voltage/high-current (LVHI) power supplies to the bifilar coil (see Fig. 2 (e) and (f)).

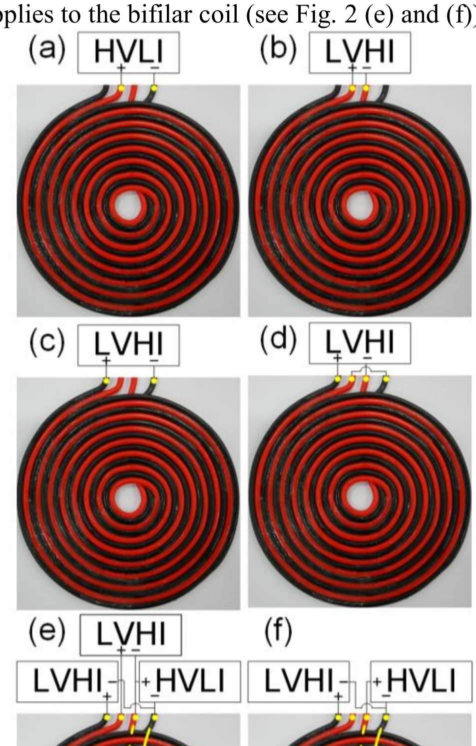

Fig. 2. Design and electric wiring of the E/MA concept. (a) Individual EA function. (b), (c), and (d) Individual EMA function. (e) and (f) Simultaneous EA and EMA function.

B. Fabrication

The fabrication of the E/MA consists of four steps: 1) Laser cut a 5 mm thick acrylic plate into a circular shape with diameter 110 mm; 2) Adhere a pre-stretched 0.5 mm thick

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VHB 4905 double-sided adhesive membrane (3M, USA) to the acrylic plate; 3) Wind, from the center to the edges, two (one black and one red) flexible electric wires onto the VHB adhesive. The wires are made of stranded tinned copper wires insulated by PVC (RS Components Ltd., UK, 24 AWG, 7 strands, insulation wall thickness ~ 0.3 mm). Use instant glue as needed to further bond the wires together while winding; and 4) For soft and flexible grasping applications, one can peel the bonded coils from the acrylic plate, forming an inherently flexible gripper that can be used to grip flexible materials such as textiles from complex such as convex and concave surfaces (see Fig. 3 (a) and (b), and the supplementary video) and for safer interaction with objects [14]. Alternatively, the coils can be left attached to the acrylic plate, as exploited in our characterization experiments.

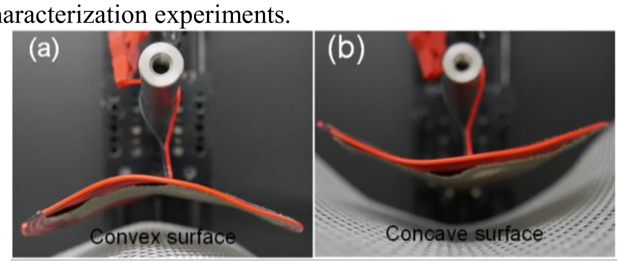

Fig. 3. Soft lifting of flexible materials from complex surfaces. (a) Lifting a textile sample from a convex surface. (b) Lifting a textile sample from a concave surface. The weight of the E/MA gripper is 24.6 g.

C. Normal EA and EMA force measurement

Individual normal electroadhesive and magnetoadhesive forces of the grippers were measured when the temperature and relative humidity were maintained at 22.5 ± 0.1 °C and 57 ± 1 % respectively. The normal adhesive forces were measured by an inline miniature S-Beam load cell (Applied Measurements Ltd., UK). When measuring the EA force, we energized the gripper using an Ultravolt high voltage amplifier (HVA, 10HVA24-BP1, Advanced Energy Industries, Inc., USA, maximum voltage 10 kV) for 20 seconds. A linear stage (X-LSQ150B-E01, Zaber Technologies Inc., USA) was used to pull the gripper away from a 20 mm thick MDF plate, in a direction normal to the surface, at the movement speed of 50 mm/s. When measuring the EMA force, the two coils were connected in series, shown in Fig. 2 (d), and the gripper was driven by a high current power supply (0-10 A adjustable power supply, CSI3010SW, Circuit Specialists Europe Ltd., UK) for 20 seconds, before the linear stage was pulled away from a magnetically susceptible steel optical breadboard (Thorlabs, USA). A NI USB-6343 X Series DAQ device (National Instruments, UK) was used to record the adhesive forces and control the supply voltages. The normal EA forces of the gripper, when applying 2 to 7 kV, can be seen in Fig. 4 (a). The normal MA forces of the gripper, when applying 4 to 10 A, can be seen in Fig. 4 (b).

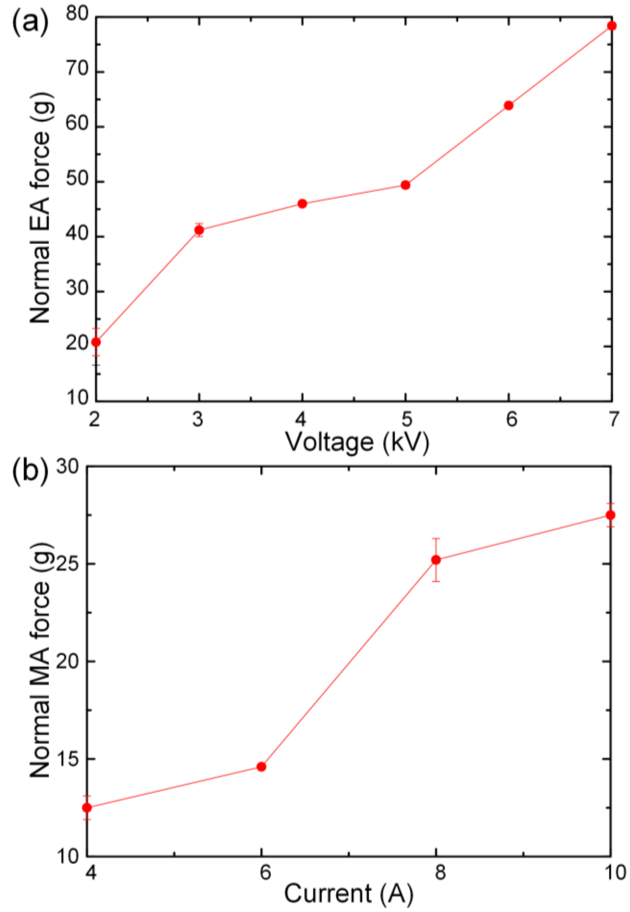

Fig. 4. Normal MA forces of two modified E/MA grippers under 4 to 10 A. All the tests were repeated five times. The error bars denote 1 standard deviation of the five results of each test.

III. Design and Development an Exteroceptive EA Material Handling System

In order to produce an autonomous and intelligent material handling system, a customized exteroceptive EA system was designed and implemented using a single HVA and without any external sensors. The two coils of the E/MA operated not only as an EA gripper, but also as an analog capacitive sensor that can indicate object contact and material difference. The E/MA was mounted on a 3D printed holder and attached to a linear stage. The operational flowchart of the system is shown in Fig. 5 (a). The system initially went to its home position. Then the baseline capacitance c_0 of the EA was measured using an embedded customized capacitance measurement method. After this, the EA was lowered and the capacitance was continuously monitored. The linear stage stopped when the capacitance reading was over a 5 % of c_0, which was generated on the fly as a function of the initial measurement and independent of the target object and proved to be enough to detect the object. Then, 4.9 kV was applied to the EA gripper to turn on the EA. The linear stage then lifted the EA gripper and object to a designated position. Finally, the EA was turned off to release the object. A customized capacitance measurement method was designed and implemented, as shown in Fig. 5 (b), where an Ultravolt 5HVA24-BP HVA was used to energize the EA gripper. An excitation signal (sine wave with an amplitude of 500 V and frequency of 80 Hz) was added to the high voltage delivered to the EA. A NUCLEO-F401RE microcontroller was used to calculate the capacitance of the EA device when approaching an object based on the current and voltage measurement values from the EA device, and provide the readings to a PC.

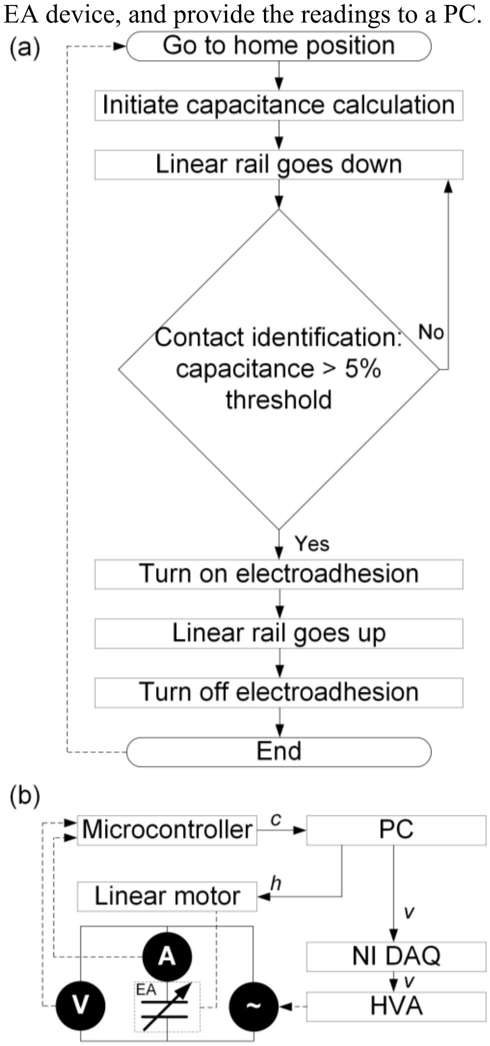

Fig. 5. Operational flowchart and schematic of the autonomous exteroceptive EA material handling system. (a) Operational flowchart. (b) Schematic diagram of the system, where V denotes voltage measurement, A denotes current measurement, *c* denotes capacitance reading, *h* denotes height information, and *v* denotes voltage output.

The EA gripper, together with the current measurement shunt resistor, when positioned in air, is essentially a variable capacitor in parallel with a resistor. We followed the self-sensing method for high voltage variable capacitors proposed by Rizzello *et al.* [15]:

$$V = Ri + \frac{1}{C}dq \tag{1}$$

$$i = \frac{dq}{dt} \tag{2}$$

where V is the measured voltage, R is the resistance, i is the measured current running through the EA device, and q is the charge stored in the EA device. We assume the capacitance, C, and R vary at least an order of magnitude slower than the sampling ratio, thus consider them to be constant, which gives:

$$\frac{dV}{dt} = R\frac{di}{dt} + \frac{1}{C}i \tag{3}$$

We then used a pre-warped Tustin method [16] to generate the differences equation (4), tuned at the sensing frequency, f_e [15]:

$$V_k - V_{k-1} = R(i_k - i_{k-1}) + \frac{K_T}{C}(i_k + i_{k-1}) \tag{4}$$

where $K_T = \frac{\tan(\pi\rho)}{2\pi f_e}$, $\rho = \frac{f_e}{f_s}$, the subscript k refers to the k^{th} sample element, and f_s is the sampling frequency.

We then applied the Recursive Least Square (RLS) method [17]:

$$\widehat{\theta_k} = \widehat{\theta_{k-1}} + H_k(Y_k - \varphi_k^T\widehat{\theta_{k-1}}) \tag{5}$$

$$H_k = \frac{P_{k-1}\varphi_k}{1+\varphi_k^T P_{k-1}\varphi_k} \tag{6}$$

$$P_k = \frac{1}{\mu}\left(P_{k-1} - \frac{P_{k-1}\varphi_k\varphi_k^T P_{k-1}}{1+\varphi_k^T P_{k-1}\varphi_k}\right) \tag{7}$$

where $Y_k = V_k - V_{k-1}$, $\varphi_k = [i_k + i_{k-1}\ i_k - i_{k-1}]^T$, $\theta_k = [C_k\ R_k]^T$, and $0 < \mu < 1$ is a forgetting factor, to be chosen such that the smaller its value, the faster convergence but with reduced filtering power.

We assume varying capacitances will be obtained when the EA gripper is approaching the object to be lifted. We used the above capacitance estimation algorithm to enable the self-sensing and autonomous gripping of fabric (0.58 g, see Fig. 6 (a)) and paper (0.20 g, see Fig. 6 (b)). The dynamic and discrete capacitance readings when the EA sensor was approaching the fabric and paper are presented in Fig. 6 (a) and (b) respectively. We then used an LCR meter (E4980AL, Keysight Technologies, USA) to measure the capacitance (under 1 V and 80 Hz) of the EA gripper in air, obtaining a value of 385.4 ± 4.6 pF. The initial capacitance value c_0 of the EA gripper as measured by the embedded algorithm on the microcontroller was 385 ± 5 pF. This confirms that the sensing system is sufficiently accurate for practical materials handling purposes. It should be noted that better hardware and more accurate capacitance calculation methods may provide better estimations, cleaner data, and allow a reduction of the 5 % threshold. Please see the supplementary video for the demonstration of autonomously grasping of fabric and paper samples using the self-sensing algorithm.

IV. Discussions

A. E/MA geometrical optimization theoretical considerations

We take two concentric wires into consideration and the cross-sectional view is shown in Fig. 7. We define r_0 as the inner diameter, r as the diameter of the wire, and w as the insulation wall thickness. The resistance of a wire can be calculated from the equation:

$$R = \frac{\rho l}{A} \tag{8}$$

where l is the length of the wire, ρ is the resistivity of the wire material (copper in this case), and A is the cross-sectional area.

The total resistance of the two concentric wires can, therefore, be written as:

$$R = \frac{4\rho(r_0 + 2w + 2r)}{r^2} \tag{9}$$

The total magnetic field at the center, when the current runs the same direction in the two wires, is:

$$B = \frac{\mu_0 I}{2}\left(\frac{1}{r_0+w+r} + \frac{1}{r_0+3w+3r}\right) \tag{10}$$

where μ_0 is the magnetic permeability of free space and I is the applied current.

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If we set the applied current and electrode resistivity as constant values, then we have:

$$\begin{cases} P \propto \frac{(r_0+2w+2r)}{r^2} \\ \sigma_{EMA} \propto \frac{1}{(r_0+4w+4r)^2-r_0{}^2}\left(\frac{1}{r_0+w+r}+\frac{1}{r_0+3w+3r}\right) \\ \sigma_{EA} \propto C\left(\frac{w}{w+r}\right) \end{cases} \quad (11)$$

where P is the power consumption, σ_{EMA} is the magnetic adhesive pressure and σ_{EA} is the electroadhesive pressure, which is related to C, a dimensionless function of geometric parameters $\frac{w}{w+r}$ [6].

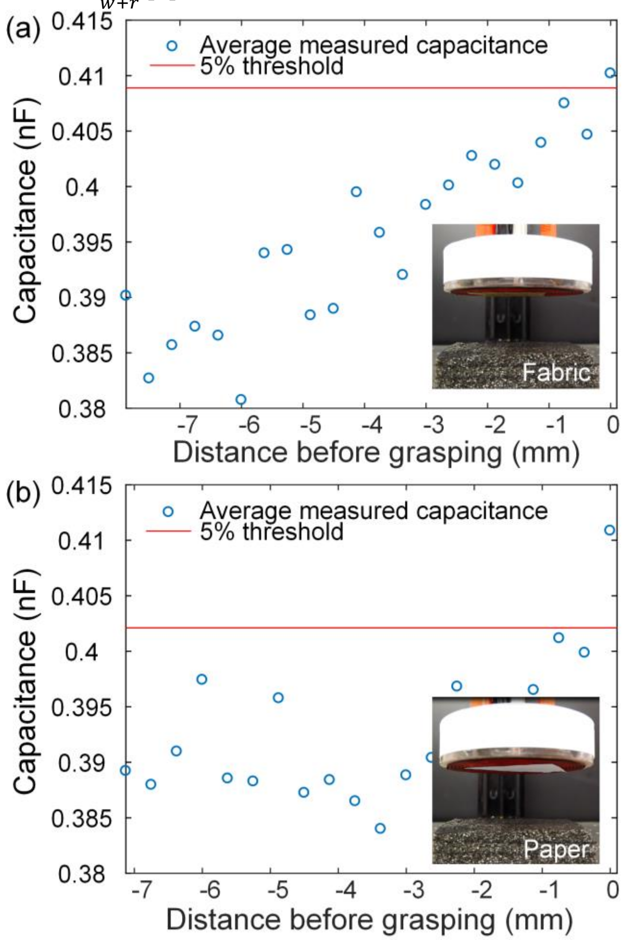

Fig. 6. Exteroceptive EA sensing results, showing capacitance readings as EA approaching samples rested on a black plastic foam. (a) Approaching a fabric sample (0.58 g). (b) Approaching a paper sample (0.20 g).

From equation (11), we can see that, in order to achieve the maximum MA forces, the wire radius and insulation wall thickness should be as small as possible. Unfortunately, the thinner wire greatly limits the maximum current (and hence the magnetic field). Further work is needed to find the optimum geometry for combined MA and EA adhesion.

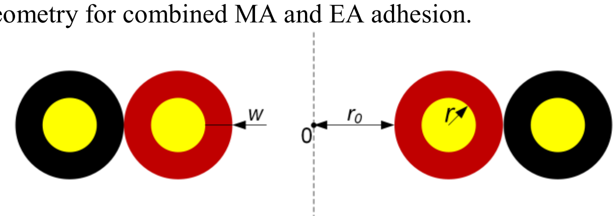

Fig. 7. Cross-sectional view of the two adjacent concentric wires.

Apart from making the wires as thin as possible, one can also add an iron core in the coil center or stack multiple layers of coils to enhance the magnitude of MA force, but at the expense of greater overall mass and thickness. Alternative E/MA fabrication methods, such as thin Kapton flexible printed circuit boards, will enable much thinner design that may greatly improve both the MA and EA forces.

B. E/MA alternative design considerations

While the simple bifilar design shown in Fig. 1 and 2 is the most elegant design, operation in the simultaneous EA and EMA mode requires that the two LVHI power supplies can operate at voltages separated by the HVLI power supply. For example, if the low voltage supplies operate at 5 V and the high voltage supply generates 5000 V, one of the LVHI power supplies must be elevated to operate at 5000 V (i.e. to generate voltage 5005 V with respect to 5000 V). Due to earthing constraints in the laboratory equipment we were not able to test the design in Fig. 2 (e) in full E/MA mode. Instead, we modified the design (see Fig. 8 (a)) such that only one low voltage power supply is needed to deliver a high current to the red coil, and it can operate together with the high voltage supply to deliver an E/MA gripper that can simultaneously lift non-ferrous textiles and ferrous paper clips, as shown in Fig. 1 (c) and Fig. 2 (f).

We compared the MA force of inner red wire part and the red wire part the modified E/MA design. The results presented in Fig. 8 (b) valid that: 1) the larger the r_0, the smaller the MA force and 2) the MA force of the outer red wire part from diameter 22 mm to 52 mm is negligible compared to the inner red wire part up to diameter 22 mm. To achieve the largest EA forces, however, it is necessary to have a larger overall coil diameter.

C. Magnetic field distribution simulation

We used the Finite Element Method Magnetics (FEMM) to model the magnetic field distribution of our coil design. 24 AWG wire was used and 10 A was applied to the coil. We set the coil outer diameter of 52 mm and inner diameter of 0. As shown in Fig. 9, the magnetic field strength along the top of the coil shows a sharp decrease from center to 52 mm, if neglecting the edge effect. Also, there is a four-time difference in the coil center magnetic field strength between 20 and 40 turns.

V. Conclusions

We have proposed the novel combination of electromagnetic adhesion and electroadhesion to form flexible hybrid adhesion grippers for more versatile gripping applications. We have demonstrated and characterized two easy-to-implement and cost-effective E/MA planar grippers. Key findings include: 1) Different adhesion modes were achieved by selectively powering the planar coils. The E/MA grippers were able to lift both magnetically susceptible (such as paper clips) and insusceptible (such as fabric) objects simultaneously; 2) The E/MA grippers were flexible and could adapt to lift flexible objects such as textiles from both convex and concave surfaces, and soft for safer interaction with delicate objects; 3) The proposed self-sensing algorithm was accurate; and 4) There is a balance between maximizing the EA and MA forces and

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minimizing the power consumption of the E/MA design. The proposed Electro-Magneto-adhesive structures have the potential to increase the effectiveness of both EA and MA in robotic material handling applications.

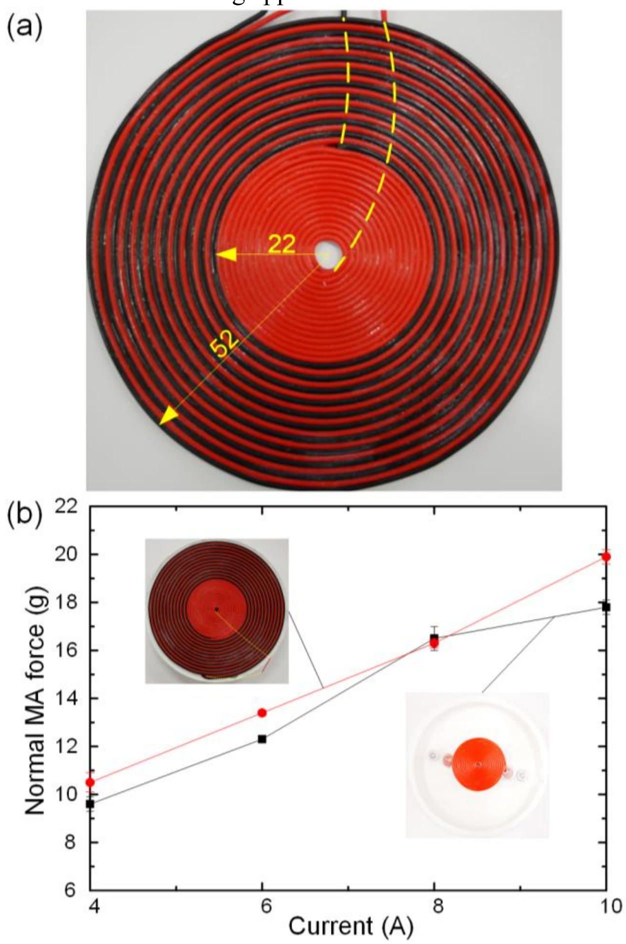

Fig. 8. The modified E/MA design. (a) The modified E/MA design with inner red wire diameter of 22 mm and overall diameter of 52 mm. (b) Comparison of the normal MA forces of the inner red and red wire of the modified E/MA design.

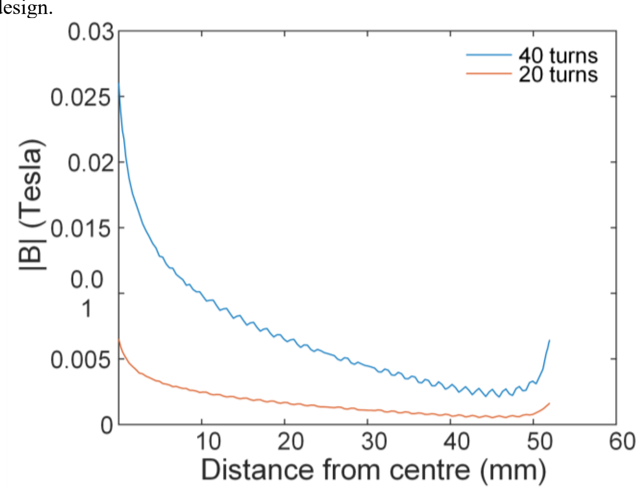

Fig. 9. Magnetic field distribution FEA simulation of a 40 and 20 turn coil.

Future work will include: 1) Investigating new fabrication solutions to deliver thinner and flexible E/MA coils with greater turns (via flexible electronics technologies) and fully-soft E/MA devices (via 3D printing liquid metals into elastomers and by simply embedding commercial electromagnets into soft EAs); 2) Investigating the scalability of the E/MA technology; 3) Developing both capacitive and inductive exteroceptive sensing functionality for more versatile material sorting capabilities; and 4) Investigating the coupled interaction between the EA and MA.

Data necessary to support conclusions are included in the article and the supplementary video.

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